ARMY RESEARCH LABORATORY

Measurement of Energy Expenditure on the Uniport Mobility Platform

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Polar Vantage XL® is a registered trademark of Polar Electro Oy.

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Abstract

The objective of this study was to measure energy expenditure on the Uniport mobility platform, a virtual reality device for dismounted infantry soldiers. Eight subjects performed at five grades (-5.0°, -2.5°, 0°, 2.5°, and 5.0°) at four speeds (2.5, 3.0, 3.5, and 4.0 mph). An Oxylog® device was used to measure oxygen uptake (VO_2). An empirical equation derived by Pandolf et al. (1977) was also used to estimate VO_2 for comparison purposes. Analysis of variance indicated that the actual VO_2 values recorded by the Oxylog were lower than the estimated VO_2 values from the Pandolf equation at 2.5° and 5.0° grades. This illustrates that the Uniport does not provide a sufficient amount of energy extraction as the grade increases and suggests that error increases as the grade increases. There were no differences between speeds for the estimated and actual VO_2, which indicates that the Uniport provides sufficient energy extraction at the speeds tested. Appropriate software or hardware adjustments must be developed on the Uniport device to increase energy output when subjects move uphill.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Jock Grynovicki for advice and assistance with the statistical analysis of the data, and they also thank the subjects for their enthusiastic participation.

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MEASUREMENT OF ENERGY EXPENDITURE ON THE UNIPORT MOBILITY PLATFORM

INTRODUCTION

Modern simulation technology is a fundamental element in maintaining readiness for war since it provides soldiers with skills and techniques that may be transferable to battlefield conditions. Modern simulation technology networks tactical engagement simulation with actual equipment, allowing realistic exercises to be conducted at a small fraction of the environmental impact and cost of field training exercises.

A recent development in simulation technology to aid the individual infantry soldier is the Uniport, developed for the U.S. Army Research Laboratory (ARL) by Sarcos Research Corporation and the Naval Postgraduate School. The Uniport is an electro-mechanical device that functions as an individual combat simulator (ICS). This system may be used with any of the Army's current or projected weapons and with any form of battle equipment for the dismounted combatant. It could allow evaluation of new materiel or new concepts within simulations of combined arms warfare. New aspects of weaponry could be explored in virtual prototype, quickly and at relatively low cost. The Uniport consists of 1) a mobility platform (similar to a unicycle) that allows the soldier to "pedal" his or her way through the virtual environment, 2) a helmet-mounted display through which the soldier sees the terrain and environment he or she will be interacting with, and 3) a model M-16 rifle (see Appendix A). Uniport allows individuals to move, shoot, communicate, be seen and heard, and interact with other objects on a simulated battlefield. In the near future, the Uniport mobility platform will be changed from the cycling-type device just described to a walking-type device.

To make the Uniport fully realistic, it will be necessary for physical exertion of the user to be similar to that experienced during an actual situation. Thus, the purpose of this study is to compare energy expenditure data generated by subjects using the Uniport with data generated by equations that estimate energy expenditure.

BACKGROUND

A method of determining expended energy or the metabolic cost of walking is done by using a standard physiological procedure known as indirect calorimetry. Indirect calorimetry is accomplished by collecting the individual's expired air and analyzing it for the volume of O_2

(VO_2) consumed and the volume of CO_2 (VCO_2) produced (Lusk, 1928). An oxygen monitor, such as an Oxylog® or similar device, consisting of a full face mask tethered to the monitor, is used to measure the number of breaths and inspiratory and expiratory VO_2. The difference between the inspiratory and expiratory VO_2 (corrected for the relative oxidation of fats and carbohydrates) yields the individual's consumed VO_2.

The measured oxygen consumption provides a close estimate of energy expenditure (McArdle, Katch, & Katch, 1991). These estimates, however, can be affected by two factors: 1) the measured VO_2 will be less than the estimated VO_2, if a steady state is not reached, and 2) exercise at maximal or near maximal intensities will involve both aerobic and anaerobic components, resulting in an over-estimation attributable to unknown contribution of the anaerobic component to the exercise (American College of Sports Medicine, 1991).

Measuring VO_2 is not always convenient because of the equipment and skills necessary to obtain it. This has prompted an interest in determining other reliable methods of predicting energy cost. As a result, several empirical equations have been developed to predict energy cost by using the speed of walking, the weight of the body and the load, and the gradient (Pandolf, Givoni, & Goldman, 1977; ACSM, 1991; Wanta, Nagle, & Webb, 1993).

ACSM Equation

The American College of Sports Medicine (ACSM) has reported an equation to estimate energy expenditure for a variety of activities including walking, running, and stepping. This formula is broken into three components: horizontal, vertical (resistive), and resting.

$$VO_2 = \underbrace{(Speed\ x\ 0.1)}_{\text{Horizontal}} + \underbrace{(Grade\ x\ Speed\ x\ 1.8)}_{\text{Vertical}} + \underbrace{3.5}_{\text{Resting}} \tag{1}$$

The formula can be simplified if the calculations involve only estimating energy expenditure for horizontal locomotion (no grade). (There are two constants in the ACSM equation, $0.1\ ml \bullet kg^{-1} \bullet \min^{-1}$ and $1.8\ ml \bullet kg^{-1} \bullet \min^{-1}$. These values were validated by the present authors and are presented in Appendix B).

$$VO_2 = (Speed\ x\ 0.1) + 3.5 \qquad (2)$$

$$\underset{\text{Horizontal}}{\Uparrow} \qquad \underset{\text{Resting}}{\Uparrow}$$

The units for VO_2 are in $ml \bullet kg^{-1} \bullet \min^{-1}$. The O_2 cost of horizontal walking is $\left(\frac{0.1\ ml \bullet kg^{-1} \bullet \min^{-1}}{m \bullet \min^{-1}}\right)$ and the O_2 cost of vertical work is $\left(\frac{1.8\ ml \bullet kg^{-1} \bullet \min^{-1}}{m \bullet \min^{-1}}\right)$. The resting component is $3.5\ ml \bullet kg^{-1} \bullet \min^{-1}$ (ACSM, 1991). The units for speed are $m \bullet \min^{-1}$, and grade is a percentage.

Although VO_2 estimates for walking are relatively accurate for most speeds and grades, there are exceptions. For example, the formula is more accurate in estimating VO_2 when the individual is walking up a grade than when walking on a level plane. Underestimations of 15% to 20% are expected with level walking and 5% to 8% for walking up a 3% grade. VO_2 can be estimated with reasonable accuracy for speeds as high as 134 $m \bullet min^{-1}$ (5 $mi \bullet h^{-1}$) and even for speeds as low as 80 $m \bullet min^{-1}$ (3 $mi \bullet h^{-1}$) (ACSM, 1991).

Pandolf Equation

Pandolf et al. (1977) also developed an equation to estimate energy expenditure for walking and running with and without loads. This equation included factors such as body weight plus external load, velocity, gradient, and type of surface (terrain factor).

$$M = 1.5(W) + 2.0(W + L)(L / W)^2 + n(W + L)(1.5V^2 + 0.35VG) \qquad (3)$$

M = metabolic rate (Watts)	W = subject mass (kg)
L = external load (kg)	n = terrain factor
V = velocity (m•sec)	G = grade (percent)

The terrain factor for this equation were empirically derived by Pandolf et al. to allow for more accurate prediction of energy expenditure. Firm walking surfaces appear to impact energy expenditure only slightly. Surfaces that allow penetration (e.g., loose sand and soft snow) alter energy expenditure more dramatically (Pandolf et al., 1977). Following are some of the terrain factors derived by Pandolf. For the purposes of this experiment, we used a terrain factor of 1.0, which is equivalent to that of treadmill walking.

Blacktop Surface	$\eta = 1.0$
Dirt Road	$\eta = 1.1$
Hard Packed Snow	$\eta = 1.3$
Heavy Brush	$\eta = 1.5$
Loose Sand	$\eta = 2.1$
Soft Snow (25 cm)	$\eta = 3.3$
Soft Snow (35 cm)	$\eta = 4.1$

Downhill Equation

A separate equation was needed to estimate the VO_2 consumption for downhill walking since neither the ACSM nor the Pandolf equation accurately does this. Wanta et al. (1993) investigated the effects of progressive downhill treadmill walking on energy expenditure using various negative grades (0%, -3%, -6%, -9%, -12%, -15%, -18% or 0°, -1.7°, -3.4°, -5.1°, -6.8°, -8.5°, -10.2°) at speeds of 3.4 mph and 3.9 mph (90 and 105 $m \bullet min^{-1}$). The relationship between VO_2 and grade for downhill walking was described by the following equations:

$$VO_2 = 10.488 + 0.73914X + 0.033132X^2 \qquad for\ 3.4\ mi \cdot h^{-1} \qquad (4)$$

$$VO_2 = 13.319 + 0.90949X + 0.039025X^2 \qquad for 3.9\ mi \cdot h^{-1} \qquad (5)$$

in which VO_2 is in $ml \bullet kg^{-1} \bullet min^{-1}$ and X represents percent grade.

We estimated energy expenditure at speeds of 2.5 and 3.0 mph for grades -2.5° and -5.0° using the energy cost curve developed by Wanta et al. (1993) and extrapolating using Y = mx+b. The extrapolated numbers for 2.5 mph and 3.0 mph were not used in the analysis. These values were calculated, assuming linearity, and fall outside the range of speeds used by Wanta et al. (1993). These extrapolated values were used only for observation.

OBJECTIVE

The purpose of this study was to calculate estimated values of energy expenditure using the ACSM, Pandolf et al., and Wanta et al. equations and to compare these values to direct measures of energy expenditure obtained while subjects are performing activity on the Uniport device.

METHODS

Equipment

The main apparatus consisted of

1. Uniport mobility platform (see Appendix C)
2. Video monitor to display terrain and speed
3. Metronome to control speed
4. Oxylog2® device to measure 0_2 consumption (see Appendix D)
5. Polar® device to measure heart rate
6. Scale to weigh each subject

Participants

Eight male soldiers volunteered to be subjects. They were briefed about the purposes and risks of the study and gave their written voluntary informed consent to participate. The investigators have adhered to the policies for the protection of human subjects as prescribed in AR 70-25. All subjects were cleared for the study by a medical record screening. Subjects were asked to provide their height and were then weighed. Subject data are shown in Table 1.

Table 1

Participant Data
(age, height, and body mass)

									Mean	SD[a]
Age (yr.)	27	34	31	33	30	35	35	34	32.4	2.83
Height (cm)	165	188	188	178	185	178	180	183	180.6	7.48
Body mass (kg)	78.6	89.5	98.6	81.8	105.9	87.7	88.6	94.1	90.6	8.82

Note. For the purposes of this study, no load was used.
[a]SD = standard deviation

Procedures

Subjects were fitted with a Polar® device to monitor their heart rate throughout the duration of the study. This device consists of a chest strap and a watch. The chest strap detects the heart impulses and transmits them via telemetry to the watch which displays the heart rate in beats per minute.

The Oxylog2® device (PK Morgan, Chatham, United Kingdom) was designed to measure oxygen consumption (VO_2) and ventilation (V_E) in ambulatory subjects. The subjects' expired air was passed to the central Oxylog2® unit which contained a FIGARO KE-25 oxygen fuel-type cell. The difference in volume of oxygen between the inspired and expired gases was measured in the instrument, and the volume of oxygen extracted was calculated. A turbine flow meter attached to the air intake side calculated the volume of the subjects' inspired air. A display on the device provided the VO_2 and V_E, which were averaged as minute values. The Oxylog2® mask was placed over the subject's mouth and nose and adjusted to obtain a proper seal. The seal assured that all expired gases entered the device. Two different sized masks were used to fit the various facial sizes and shapes of the subjects. The subject mounted the Uniport to start the test. A baseline VO_2 reading was first recorded by having the subject breathe normally while sitting on the Uniport and not pedaling (see Appendix C).

Subjects were told to traverse at four different speeds (2.5 mph, 3.0 mph, 3.5 mph, and 4.0 mph) along five different grades (0°, 2.5°, 5.0°, -2.5°, -5.0°) that were displayed on the monitor. Subjects followed the same order of testing as shown in Table 2; speeds and grades were not randomized. A metronome allowed the subject to maintain a constant speed by synchronizing the pedal strokes with a constant beat. The beats per minute were predetermined for each speed. Subjects began the test by traversing the 0° grade at a speed of 2.5 mph for approximately 3 to 4 minutes until their VO_2 reached a plateau. VO_2 readings were recorded every minute. Subjects were then asked to increase their speed to 3.0 mph for the same approximate time still on the 0° grade. The subject remained on the 0° grade until he finished traversing that grade at all four speeds. The subject then dismounted the Uniport and rested for approximately 10 minutes. The same procedure was followed for the each of the remaining grades at each speed.

Table 2

Experimental order for grade and speed

Grade (degrees)	Speed (mph)
0	2.5, 3.0, 3.5, 4.0
2.5	2.5, 3.0, 3.5, 4.0
5.0	2.5, 3.0, 3.5, 4.0
-2.5	2.5, 3.0, 3.5, 4.0
-5.0	2.5, 3.0, 3.5, 4.0

DATA ANALYSIS

Approximately four readings were taken for every subject at each speed and grade combination (one reading per minute). These readings were averaged and divided by their weight to determine the subject VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$). Means and standard deviations were calculated for the actual VO_2 values, Pandolf estimated VO_2 values, and ACSM estimates. Differences between the actual VO_2 values and Pandolf estimates were compared using a repeated measures analysis of variance (ANOVA) in order to look more closely at speed and grade interactions. The VO_2 values from the ACSM equation were not used in the analysis because it is a point estimation with no variance. The ACSM values are included in Table 3 and Figure 1 for comparison.

RESULTS

The mean actual VO_2 and the estimated VO_2 for the positive grades are shown in Table 3 and Figure 1.

Table 3

VO$_2$ for Positive Grades
(estimated VO$_2$ calculated from ACSM equation [ACSM, 1991] and Pandolf [1977])

		Grade = 0°				Grade = 2.5°				Grade = 5.0°			
	Rest mph	2.5 mph	3.0 mph	3.5 mph	4.0 mph	2.5 mph	3.0 mph	3.5 mph	4.0 mph	2.5 mph	3.0 mph	3.5 mph	4.0 mph
Actual VO$_2$ mean (ml•kg^{-1}•min^{-1})	3.86	10.7	13.4	17.1	20.6	13.6	15.5	18.7	23.4	14.8	18.2	21.9	26.8
Standard deviation	0.67	1.37	1.86	2.96	3.56	2.22	2.13	2.50	4.54	1.45	1.63	2.71	3.33
ACSM estimate (ml•kg^{-1}•min^{-1})	3.5	10.2	11.5	12.9	14.2	15.5	17.8	20.3	22.6	20.7	24.1	27.6	31.0
Difference (percent) Act. vs. ACSM	9.3	4.7	14.2	24.6	31.1	-14.0	-14.8	-8.6	3.4	-39.9	-32.4	-26.0	-15.7
Pandolf estimate** (ml•kg^{-1}•min^{-1})	4.4*	10.0	12.4	15.3	18.7	15.1	18.5	22.4	26.8	20.2	24.6	29.5	35.1
Difference (percent) Act. vs. Pandolf	-14.5	6.5	7.5	10.5	9.2	-11.0	-19.4	-19.8	-14.5	-36.5	-35.2	-34.7	-30.9

* Pandolf estimate for rest calculated from mean weight of all subjects
** Data from Pandolf were converted from watts to ml•kg^{-1}•min^{-1} (McArdle, Katch, & Katch, 1991)

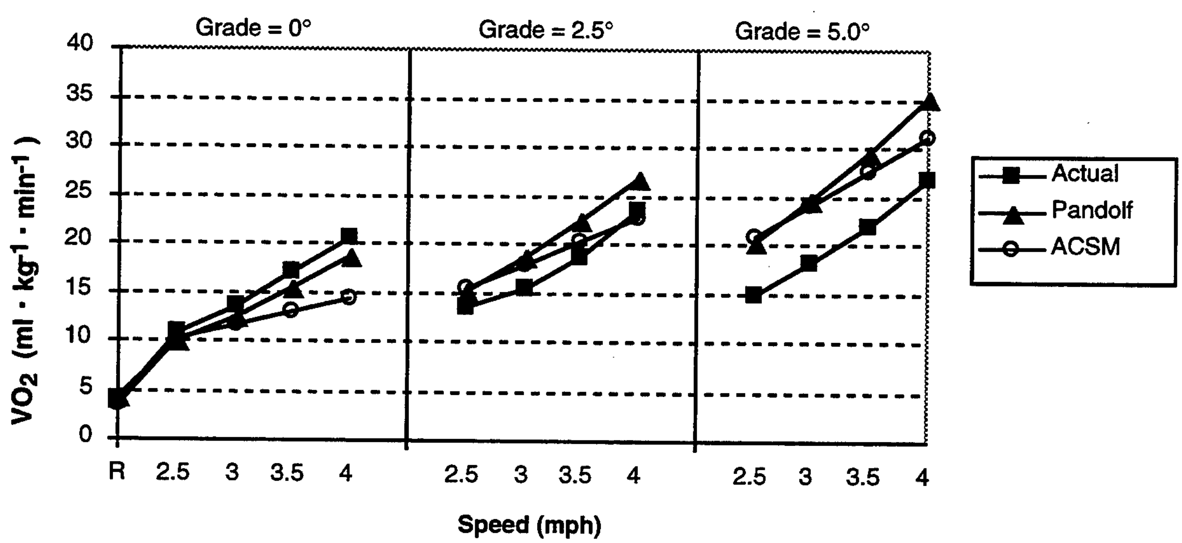

Figure 1. Mean actual VO$_2$ and estimated VO$_2$ from Pandolf et al. (1977) and the ACSM (1991) for positive grades.

The mean actual VO_2 and the estimated VO_2 for the negative grades are shown in Table 4 and Figure 2. The negative grades were not included in the ANOVA, they are shown for observation only.

Table 4

VO_2 for Negative Grades
(estimated VO_2 calculated from Wanta equation [Wanta et al., 1993])

	Grade = -2.5°				Grade = -5.0°			
	2.5 mph	3.0 mph	3.5 mph	4.0 mph	2.5 mph	3.0 mph	3.5 mph	4.0 mph
Actual VO_2 mean ($ml{\bullet}kg^{-1}{\bullet}min^{-1}$)	10.16	12.31	14.75	17.70	9.15	10.56	13.21	16.31
Standard deviation	1.24	1.23	1.58	2.34	1.05	0.65	1.19	2.31
Wanta estimate ($ml{\bullet}kg^{-1}{\bullet}min^{-1}$)	3.7*	5.9*	8.1	10.3	3.2*	5.0*	6.8	8.6
Difference (percent) Act. vs. Est. VO_2	-	-	45.08	41.81	-	-	48.52	47.27

* Extrapolated values for observation only (not included in analysis)

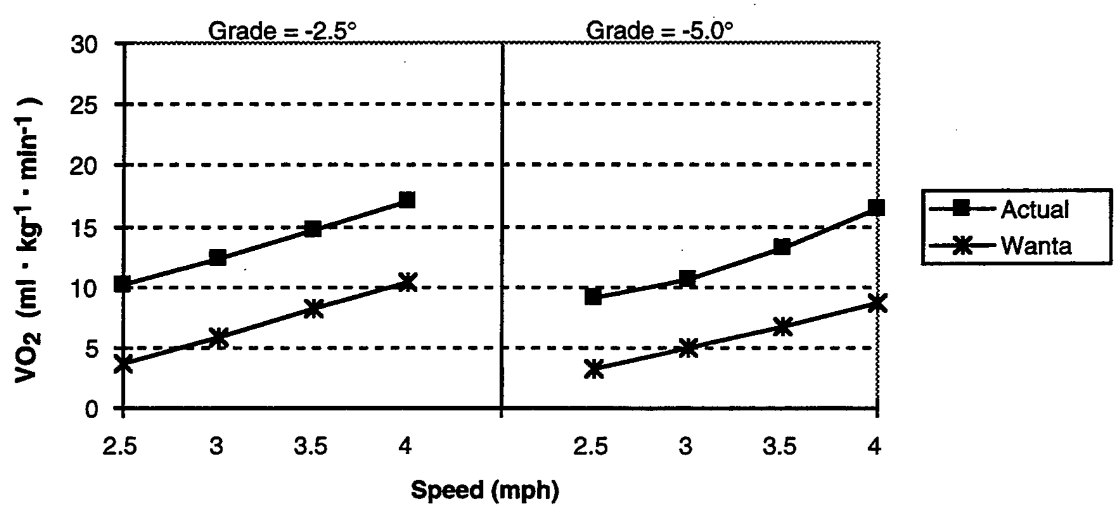

Figure 2. Mean VO_2 observed versus VO_2 predicted from the Wanta equation for negative grades.

An ANOVA performed on the VO_2 for positive grades revealed a significant main effect for Pandolf versus actual VO_2, $F(1,7) = 17.14, p = .004$. There were also significant main effect differences between speeds, $F(3, 21) = 483.47, p < .01$ and grades, $F(2, 14) = 283.28, p < .01$. There was a significant Pandolf versus Actual x Grade interaction, $F(2, 14), = 57.49, p < .01$ as illustrated in Figure 3. This illustrates that as grade increases, VO_2 estimates from the Pandolf equation rise more rapidly than the actual VO_2.

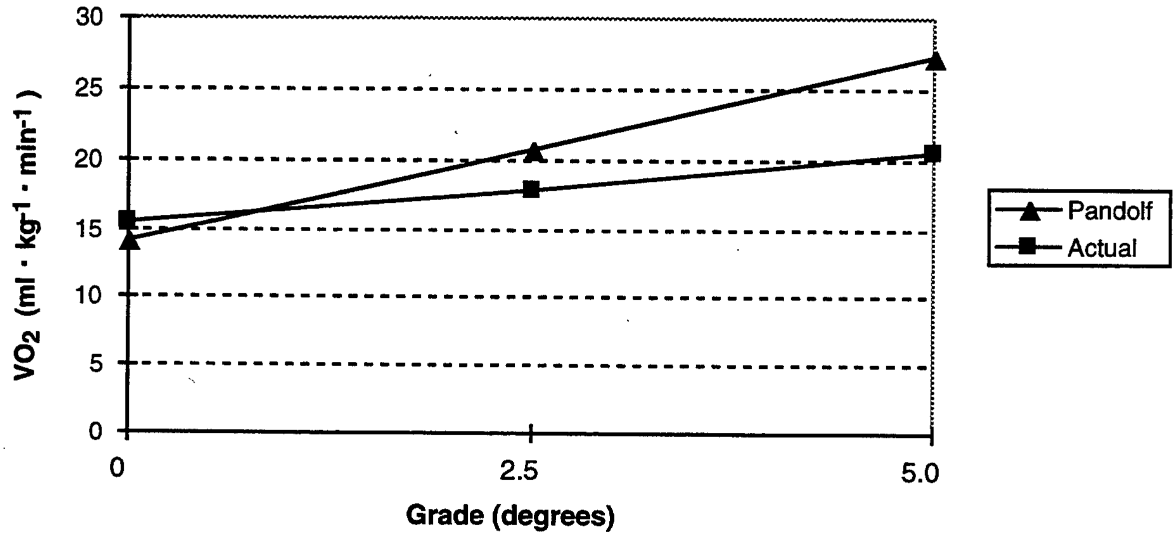

Figure 3. Pandolf versus Actual x Grade interaction.

There was no significant Pandolf versus Actual x Speed interaction, $F(3, 21) = 1.43, p = .26$, but there was a Grade x Speed interaction, $F(6, 42) = 19.44, p <.01$ as illustrated in Figure 4.

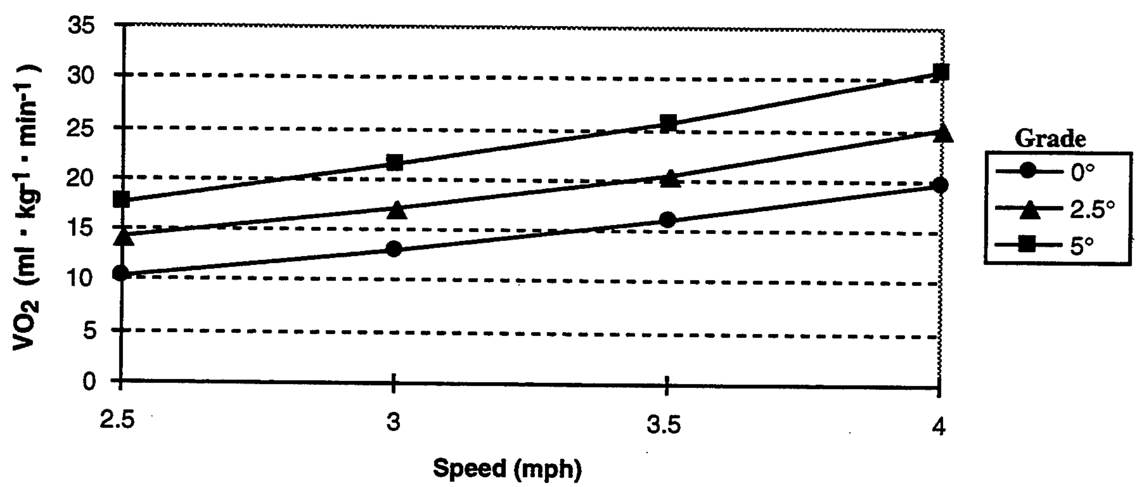

Figure 4. Grade x Speed interaction.

There was a significant three-way interaction for Pandolf versus Actual x Grade x Speed, $F(6, 42) = 6.22, p < .01$ as illustrated in Figure 5.

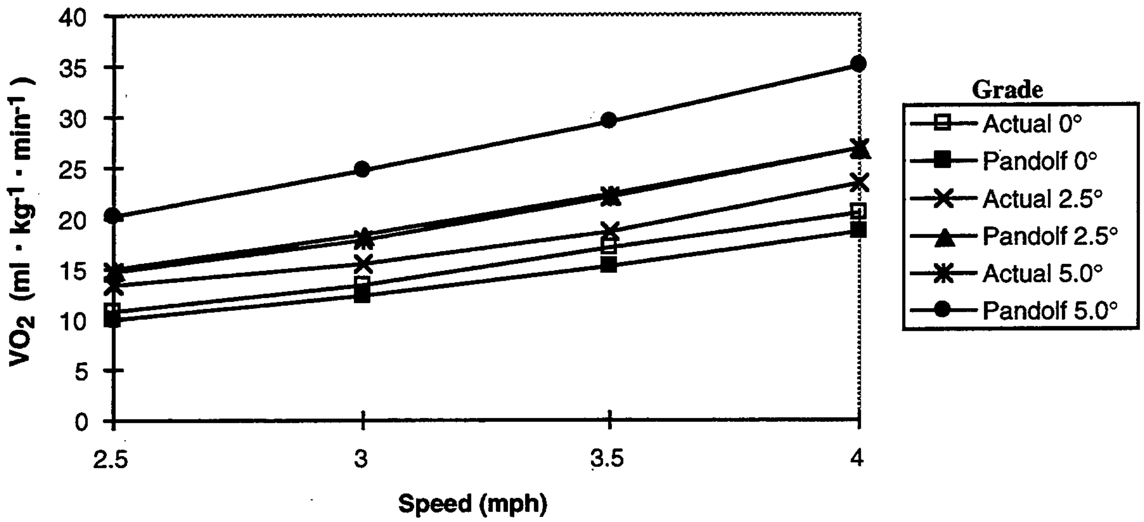

Figure 5. Three-way interaction for Pandolf versus Actual x Grade x Speed.

DISCUSSION

The results of the ANOVA are shown in Figures 3, 4, and 5. Figure 3 shows that the actual VO_2 values recorded by the Oxylog are lower than the estimated VO_2 values from the Pandolf equation at 2.5° and 5.0° grades. This illustrates that the Uniport does not provide a sufficient amount of energy extraction as the grade increases and suggests that error increases as the grade increases. As indicated in the results, there was no significant Pandolf versus Actual x Speed interaction, which illustrates that the Uniport provides sufficient energy extraction at the speeds tested.

Also striking is the fact that in downhill movement there were large discrepancies between the actual energy cost on the Uniport and values calculated from the Wanta equation as shown in Figure 2. These mismatches ranged from 40% to 50% with the actual VO_2 values higher than the Wanta estimates. There was, however, a 20% to 40% decrease in VO_2 when actual VO_2 values were compared at positive and negative grades and a 14% decrease in VO_2 when actual VO_2 values were compared at the 0° grade to actual VO_2 values for negative grades, indicating that the Uniport did attempt to simulate downhill walking (see Figures 1 and 2).

Overall, these results indicate that further research must be conducted to determine how to change energy cost as grade is changed. Energy extraction must be increased on the uphill and

decreased on the downhill. Downhill energy cost will be particularly difficult to simulate since the relationship between energy cost and negative grade is not linear (Wanta et al., 1993). The Wanta equation provides oxygen uptake but the relationship between effort felt and energy expenditure would have to be programmed into the Uniport's software to obtain a more accurate measure of energy cost. The results from this test will serve as a baseline for adjusting the Uniport's software and hardware for a higher precision of energy extraction.

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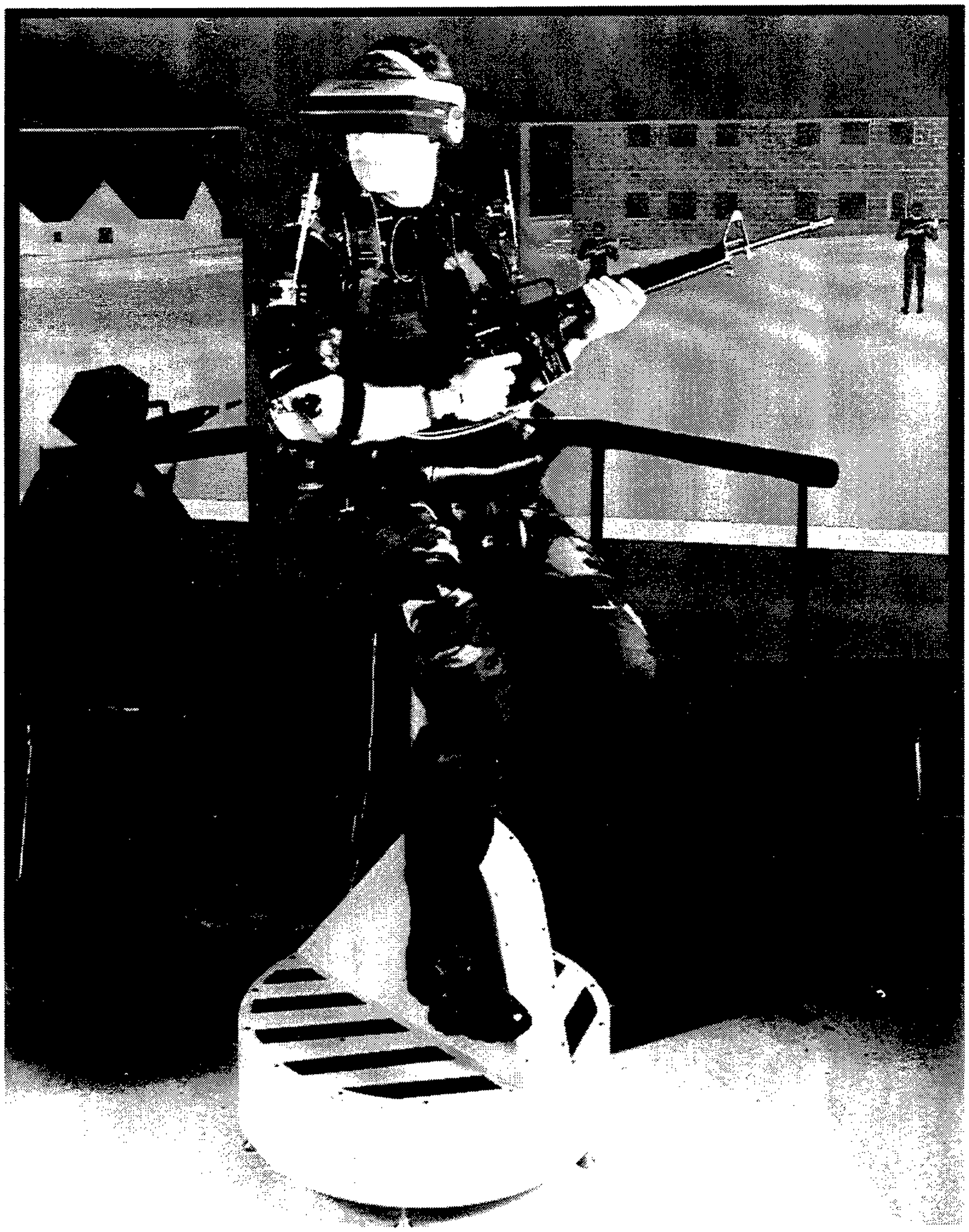
APPENDIX A

UNIPORT WITH MODEL M16 RIFLE

UNIPORT WITH MODEL M16 RIFLE



APPENDIX B

VALIDATION OF ACSM EQUATION

VALIDATION OF ACSM EQUATION

The constants from the ACSM equation were validated by the present authors against energy expenditure data obtained in previous studies. The data used to validate the horizontal component were taken from Duggan and Haisman (1992) and Jones, Toner, Daniels, and Knapik (1984). In these studies, subjects performed level walking on the treadmill at different speeds. A horizontal component (HC) was calculated for each subject by plugging the given data into the ACSM equation and solving for HC. Additional load carried by subjects was added to the total body weight (Soule, Pandolf, & Goldman, 1978; Goldman & Iampietro, 1962).

$$VO_2 = (Speed \; x \; HC) + 3.5 \tag{6}$$

$$HC = \frac{(VO_2 - 3.5)}{Speed} \tag{7}$$

Results of the horizontal component calculations are shown in Table B-1. The results from this empirical validation indicate that the ACSM estimate of 0.1 for the horizontal component of the equations is a close approximation, although it tends to slightly underestimate the values of Duggan and Haisman (1992) and Jones et al. (1984).

Table B-1

Horizontal Component Calculations

Speed ($m \cdot min^{-1}$)	Subject body mass (kg)	Load mass carried (kg)	VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)	Horizontal component
		Duggan & Haisman 1992		
99.23	70.42	4.09	12.74	0.13
99.23	70.42	24.71	12.06	0.12
99.23	70.42	24.68	12.9	0.13
99.23	63.49	26.92	13.8	0.14
99.23	63.44	29.70	13.9	0.14
99.23	63.60	29.62	13.5	0.14
		Jones et al., 1984		
67.0	75.1	0	7.00	0.10
67.0	75.1	0	7.6	0.11
93.8	75.1	0	10.7	0.11
93.8	75.1	0	11.9	0.13

Note. The VO_2 data are with the resting component, 3.5, already subtracted.

To validate the vertical component (VC), data were taken from Pimental, Shapiro, and Pandolf (1982). In this investigation subjects walked on level and uphill grades with or without loads. Similar to the calculations for the HC, VO_2, speed, weight, and load were used in addition to grade for calculating the VC.

$$VO_2 = (Speed\ x\ 0.1) + (Grade\ x\ Speed\ x\ VC) + 3.5 \tag{8}$$

$$VC = \frac{(VO_2 - 3.5) - (Speed\ x\ 0.1)}{(Grade\ x\ Speed)} \tag{9}$$

The results of vertical component calculations are shown in Table B-2.

Table B-2

Vertical Component Calculations

Speed ($m \bullet min^{-1}$)	Weight (kg)	Load (kg)	Grade (percent)	VO_2 ($ml \bullet kg^{-1} \bullet min^{-1}$)	Vertical component
			Pimental et al., 1982		
40.2	70.4	0	10	6.94	1.72
40.2	70.4	0	30	20.06	1.66
40.2	70.4	15.0	5	3.27	1.62
40.2	70.4	15.0	10	6.33	1.57
67.0	70.4	0	5	6.14	1.83
67.0	70.4	0	10	11.25	1.54
67.0	70.4	15	5	4.90	1.47
67.0	70.4	30.0	5	5.33	1.59

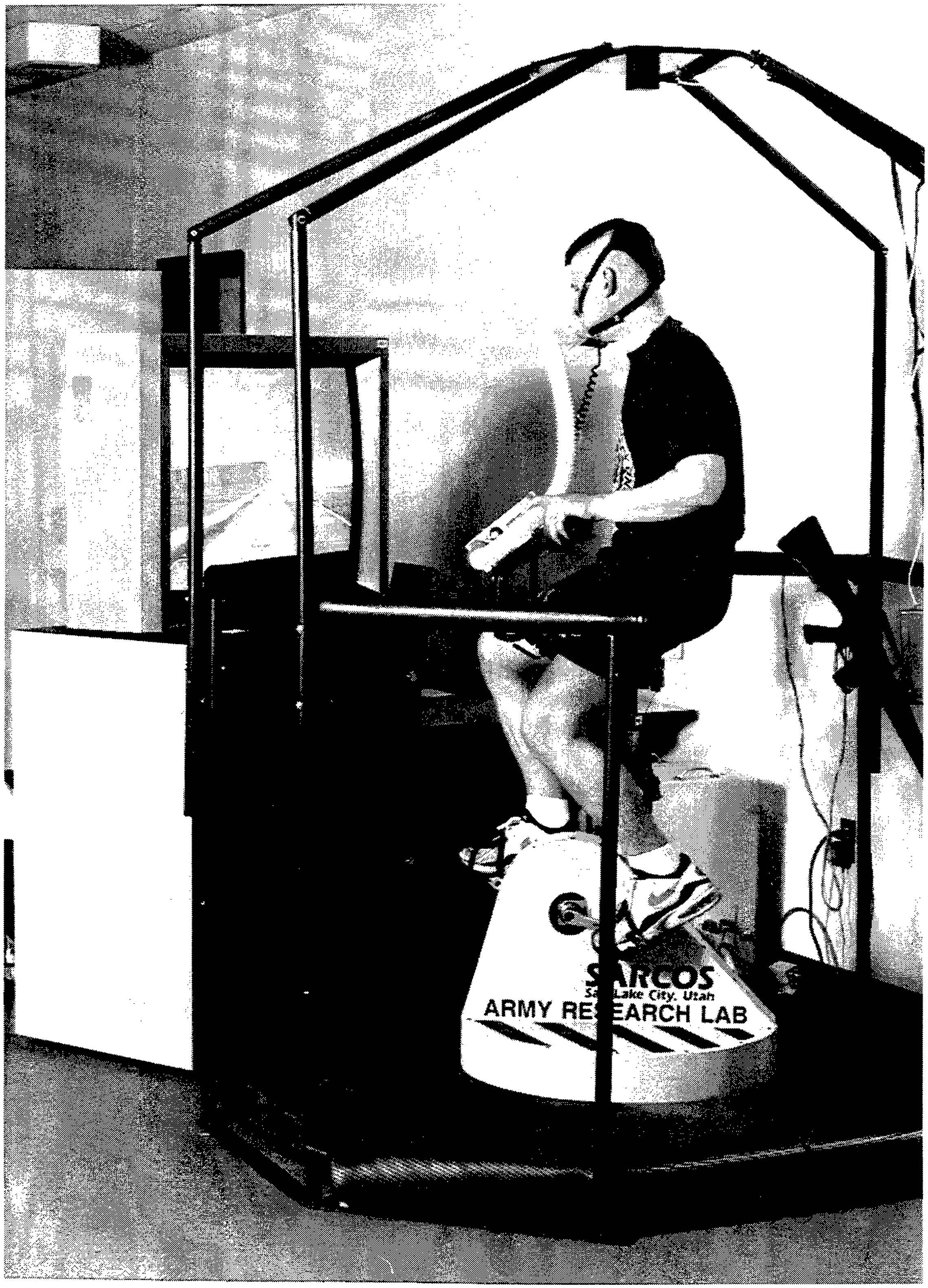
Note. The VO_2 data shown in Table B-2 are with the resting component, 3.5, and the horizontal component already subtracted.

Results indicate that the 1.8 constant for the vertical component has more variability than the horizontal component and tends to overestimate the value obtained from the Pimental et al. (1982) data. However, the constant is a close approximation for a vertical component constant.

APPENDIX C

UNIPORT MOBILITY PLATFORM

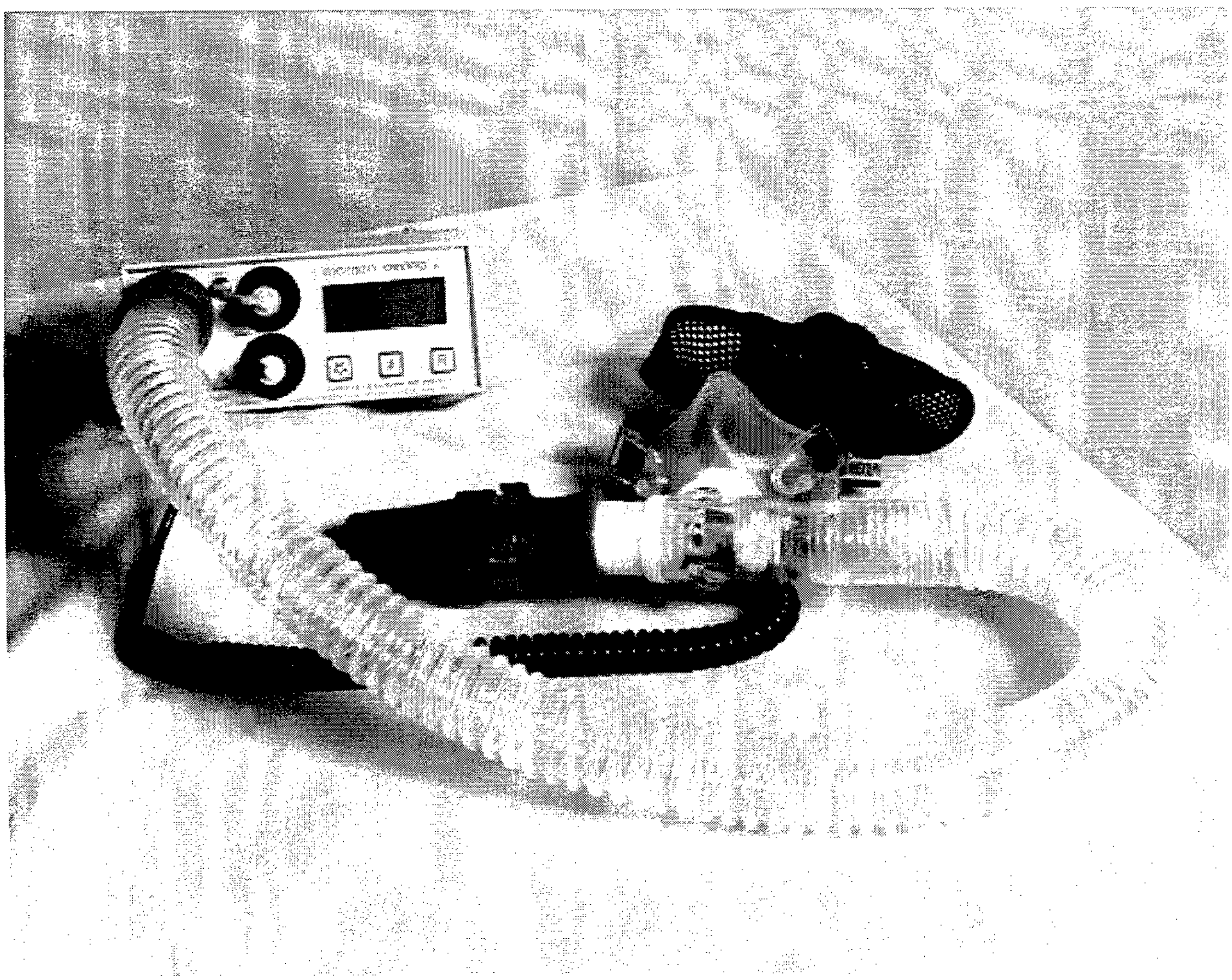
UNIPORT MOBILITY PLATFORM



APPENDIX D

OXYLOG2®

OXYLOG2®



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13. ABSTRACT *(Maximum 200 words)*

The objective of this study was to measure energy expenditure on the Uniport mobility platform, a virtual reality device for dismounted infantry soldiers. Eight subjects performed at five grades (-5.0°, -2.5°, 0°, 2.5°, and 5.0°) at four speeds (2.5, 3.0, 3.5, and 4.0 mph). An Oxylog" device was used to measure oxygen uptake (VO_2). An empirical equation derived by Pandolf et al. (1987) was also used to estimate VO_2 for comparison purposes. Analysis of variance indicated that the actual VO_2 values recorded by the Oxylog were lower than the estimated VO_2 values from the Pandolf equation at 2.5° and 5.0° grades. This illustrates that the Uniport does not provide a sufficient amount of energy extraction as the grade increases and suggests that error increases as the grade increases. There were no differences between speeds for the estimated and actual VO_2, which indicates that the Uniport provides sufficient energy extraction at the speeds tested. Appropriate software or hardware adjustments must be developed on the Uniport device to increase energy output when subjects move uphill.

14. SUBJECT TERMS

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metabolic platform	virtual reality	

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